



# Mechanical alloying and milling

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## Abstract

Mechanical alloying (MA) is a solid-state powder processing technique involving repeated welding, fracturing, and rewelding of powder particles in a high-energy ball mill. Originally developed to produce oxide-dispersion strengthened (ODS) nickel- and iron-base superalloys for applications in the aerospace industry, MA has now been shown to be capable of synthesizing a variety of equilibrium and non-equilibrium alloy phases starting from blended elemental or prealloyed powders. The non-equilibrium phases synthesized include supersaturated solid solutions, metastable crystalline and quasicrystalline phases, nanostructures, and amorphous alloys. Recent advances in these areas and also on disordering of ordered intermetallics and mechanochemical synthesis of materials have been critically reviewed after discussing the process and process variables involved in MA. The often vexing problem of powder contamination has been analyzed and methods have been suggested to avoid/minimize it. The present understanding of the modeling of the MA process has also been discussed. The present and potential applications of MA are described. Wherever possible, comparisons have been made on the product phases obtained by MA with those of rapid solidification processing, another non-equilibrium processing technique. © 2001 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

Scientific investigations by materials scientists have been continuously directed towards improving the properties and performance of materials. Significant improvements in mechanical, chemical, and physical properties have been achieved through chemistry modifications and conventional thermal, mechanical, and thermomechanical processing methods. However, the ever-increasing demands for “hotter, stronger, stiffer, and lighter” than traditional materials have led to the

### 3. Nomenclature

Two different terms are commonly used in the literature to denote the processing of powder particles in high-energy ball mills. *Mechanical Alloying* (MA) describes the process when mixtures of powders (of different metals or alloys/compounds) are milled together. Material transfer is involved in this process to obtain a homogeneous alloy. On the other hand, milling of uniform (often stoichiometric) composition powders, such as pure metals, intermetallics, or prealloyed powders, where material transfer is not required for homogenization, has been termed *Mechanical Milling* (MM). The destruction of long-range order in intermetallics to produce either a disordered intermetallic or an amorphous phase has been referred to as *Mechanical Disordering* (MD) [51]. The advantage of MM/MD over MA is that since the powders are already alloyed and only a reduction in particle size and/or other transformations need to be induced mechanically, the time required for processing is short. For example, MM requires half the time required for MA to achieve the same effect [52]. Additionally, MM of powders reduces oxidation of the constituent powders, related to the shortened time of processing [52]. Some investigators have referred to MM as *Mechanical Grinding* (MG). Since “grinding” is normally thought of as an abrasive machining process that involves mainly shear stresses and chip formation, the term “milling” is preferred to include the more complex triaxial, perhaps partly hydrostatic, stress states that can occur during ball milling of powders [5]. It should also be realized that MA is a generic term, and some investigators use this term to include both mechanical alloying and mechanical milling/disordering/grinding. However, we will distinguish between these two terms by using MA or MM depending on whether material transfer is involved or not during processing.

Some other terms are also used in the literature on Mechanical Alloying. These include reaction (or reactive ball) milling, cryomilling, rod milling, mechanically activated annealing (M2A), double mechanical alloying (dMA), and mechanically activated self-propagating high-temperature synthesis (MASHS).

*Reaction Milling* (RM) is the mechanical alloying process accompanied by a solid-state reaction and was pioneered by Jangg et al. [53]. In this process the powder is milled without the aid of any process control agent (see later for its function during milling) to produce fine dispersions of oxides and carbides in aluminum [54]. The dispersion of carbides is achieved by adding lamp-black or graphite during milling of aluminum. Adjusting the oxygen content via close control of the milling atmosphere (oxygen, argon, nitrogen, air, etc.) produces the oxides. Thus, the final product of milling contains a dispersion of  $\text{Al}_4\text{C}_3$  and  $\text{Al}_2\text{O}_3$  in an aluminum matrix and these alloys are given the trade name DISPAL. Milling of metal powders in the presence of reactive solids/liquids/gases (enabling a chemical reaction to take place) is now regularly employed to synthesize metal oxides, nitrides, and carbides [55,56]. Thus, milling of titanium in a nitrogen atmosphere has produced titanium nitride [57,58]. Several other compounds have also been produced in a similar way. Milling of tungsten with carbon (graphite) has produced tungsten carbide [59]. Milling of metal powders with boron has